Lithium and NSTX

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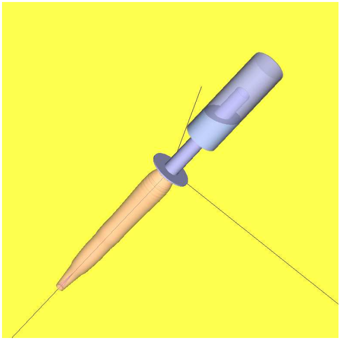
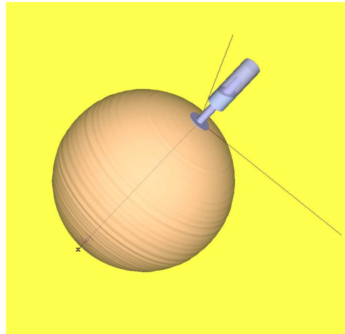
Contents

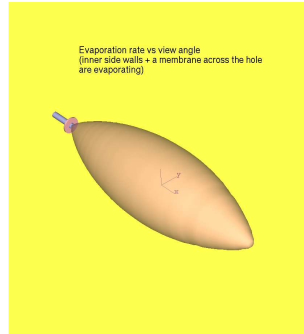
Two models for "wet" and "dry" inner walls regime are implemented into Cbebm code for calculating evaporation diagram



"Dry" model for LITER. Pipe attenuates the Li flux by 10 times



"Wet" model for LITER. Uniform temperature.



Wet snout inner walls/cold end (predictably) failed in L245

T	1/sec	g/sec	mg/min	|	1/sec	g/sec	mg/min	f
4.500e+02	8.810e+16	1.015e-06	6.093e-02	|	7.994e+17	9.213e-06	5.528e-01	0.01
5.000e+02	4.543e+17	5.236e-06	3.142e-01	|	4.122e+18	4.751e-05	2.850e+00	0.07
5.500e+02	1.923e+18	2.216e-05	1.330e+00	|	1.745e+19	2.011e-04	1.207e+01	0.28
6.000e+02	6.912e+18	7.966e-05	4.780e+00	|	6.271e+19	7.228e-04	4.337e+01	1.00
6.500e+02	2.166e+19	2.497e-04	1.498e+01	|	1.965e+20	2.265e-03	1.359e+02	3.13
7.000e+02	6.045e+19	6.967e-04	4.180e+01	|	5.485e+20	6.322e-03	3.793e+02	8.74
7.500e+02	1.528e+20	1.761e-03	1.057e+02	|	1.386e+21	1.598e-02	9.587e+02	22.1
8.000e+02	3.546e+20	4.087e-03	2.452e+02	|	3.217e+21	3.708e-02	2.225e+03	51.3

“Wet” wall regime delivers 8 times more Li than “dry”

The Knudsen gas model was adopted for the “dry” case

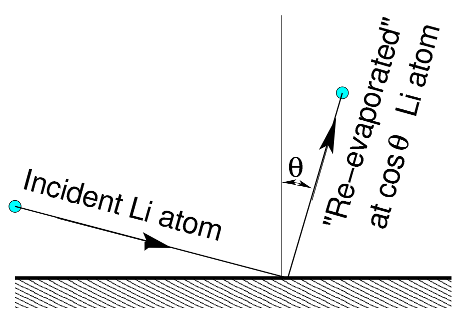
Vapor density as a function of Li surface temperature:

$$n_{20}^{vapor} = 10^{9.6-7.8\frac{1000}{T_K}}. \qquad (1.1)$$

Mean free path of Li vapor atoms

$$\lambda = \frac{1}{\sqrt{2}\pi d^2 n} = \frac{1.34}{n_{20}} \cdot \frac{4.1^2}{d^2\ [\mathrm{A}^2]}\ [\mathrm{cm}],$$

$$d_{Li} \simeq 4.1\ [\mathrm{A}]. \qquad (1.2)$$



sticking-re-evaporation as Li-LITER wall interaction

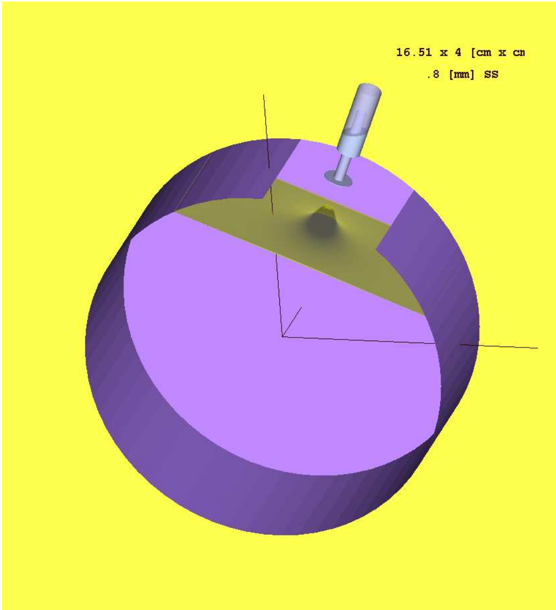
The Knudsen model is valid when

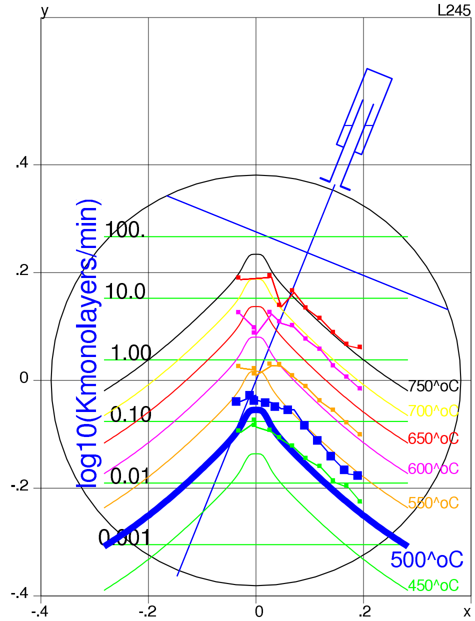
$$\lambda > L, \qquad (1.3)$$

where L represents the characteristic distances inside evaporator.

At $T > 650^o\ C$ the model is not longer applicable inside the canister

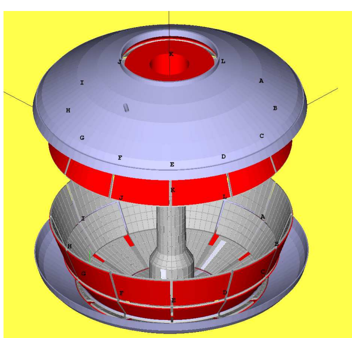
Numerical model shown an excellent reproduction of deposition profile in L245 test vessel

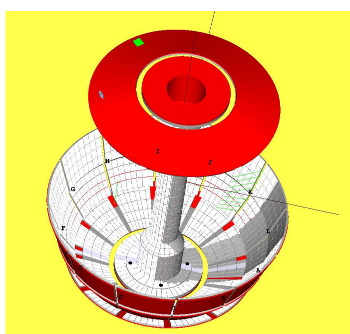


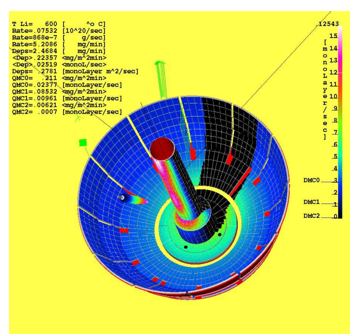


Factor of 3 in amplitude was not yet recovered, but not of concern

3D model of NSTX tiles has been created


Numerical model of NSTX PFC


Shadow of central pole


Intensity of Li deposition

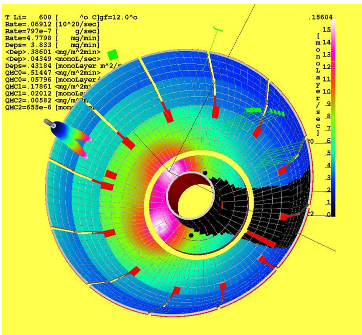
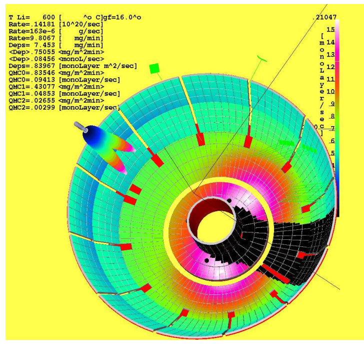
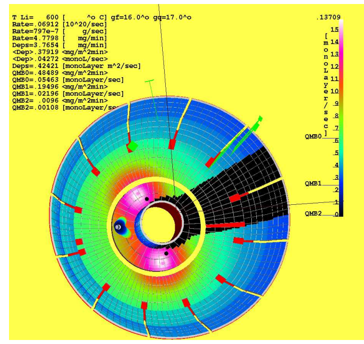
LITER-1 was capable of delivering

$$0.16 \times \text{f [mg/min]}, \quad f_{600^oC} = 1, \quad f_{800^oC} = 50 \qquad (1.4)$$

of Li to the inner low divertor tiles.

Cbebm code is quantitatively consistent with C.Skinner deposition monitor

Optimization is possible using double barrel LITER

Double barrel LITER would be capable of delivering

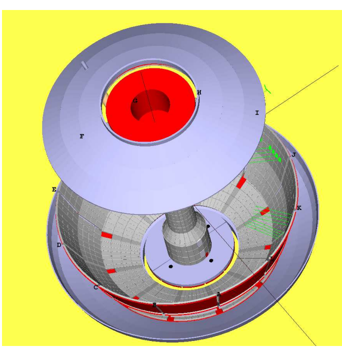
$$0.05 \times \mathtt{f} \cdot 10^{19}\ \textit{[1/sec]} = 0.05 \times \mathtt{f}\ \textit{[mono-layer/sec]},\quad f_{600^oC} = 1, \quad f_{800^oC} = 50 \tag{1.5}$$

of Li to the inner low divertor tiles. It is necessary to absorb

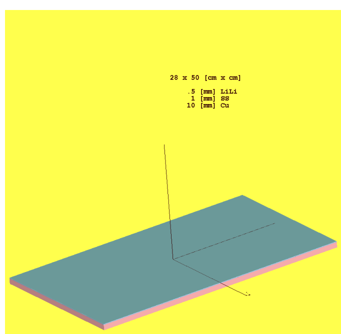
$$\frac{dN}{dt} = (400-1000) \times 10^{19}\, \frac{\textit{1}}{\textit{sec}} = (400-1000)\, \frac{\textit{mono-layer}}{\textit{sec}} \tag{1.6}$$

Even at full capacity, LITER will not be adequate for the problem

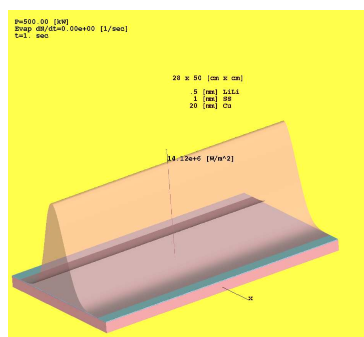
Molten Li is necessary to provide 10000 active monolayers or $\simeq 3\mu k$ of Li.



Li coated plate in low inner divertor



Li/SS/Cu (0.5mm/1mm/10mm) sandwich with a trenched surface

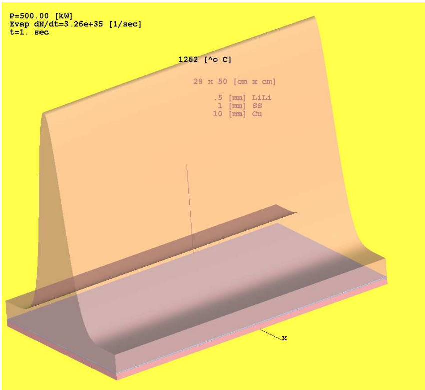


Gaussian (8 cm wide) heat deposition profile

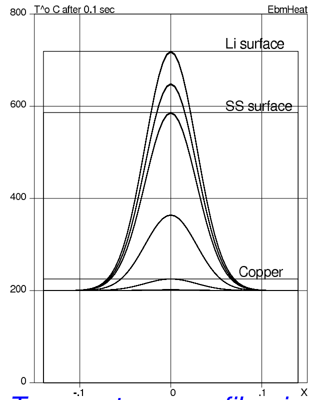
$$\begin{aligned} &S \simeq 0.75\ \textit{[m}^2\textit{]}, \quad V_{Li} \simeq 0.35\ \textit{[L]}, \quad M_{Li} \simeq 175\ \textit{[g]},\\ &\nu_{Pa\cdot sec} = 4.2 \cdot 10^{-4}, \quad I_{ion,MA} = \frac{(0.4-1)\cdot 10^{-3}}{1.6}, \quad L_{SOL,m} = 2.5,\\ &V_{Li,cm/sec} = (1-5)\cdot B_{tor} \frac{h^2_{Li,mm}}{0.01} \frac{0.1}{w_{SOL}} \frac{I_{SoL,MA}}{I_{ion}} \end{aligned} \tag{1.7}$$

Li/SS/Cu plate is an important interim step toward Li PFC

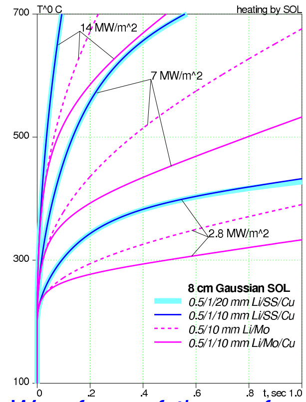
Plate can have different thermal inertia regimes



Surface temperature profile after 0.1 sec



Temperature profile inside the plate



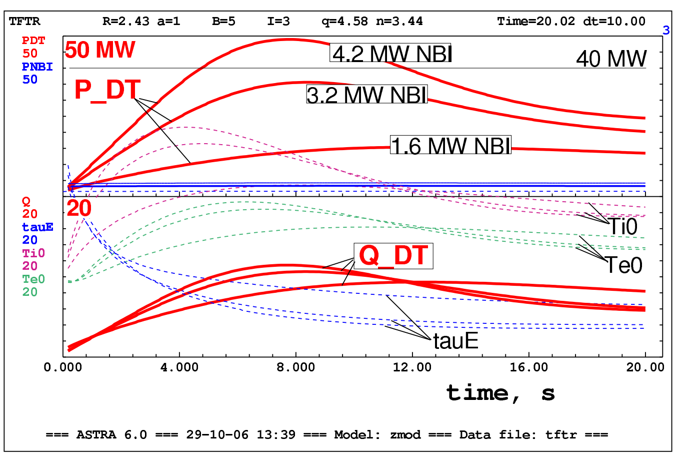
Waveform of the surface temperature

Three cases with 2.5, 1.25, 0.5 MW from the SOL to the plate

Power deposition can be used potentially for maintenance of the Li surface.

SS layer limits the heat transport into the plate body

ASTRA-ESC simulations of TFTR, B=5 T, I=3 MA, 80 keV NBI



Even with no α-particle heating:

$$P_{NBI} < 5 \text{ [MW]},$$
$$\tau_E = 4.9 - 6.5 \text{ [sec]},$$
$$P_{DT} = 10 - 48 \text{ [MW]},$$
$$Q_{DT} = 9 - 12$$

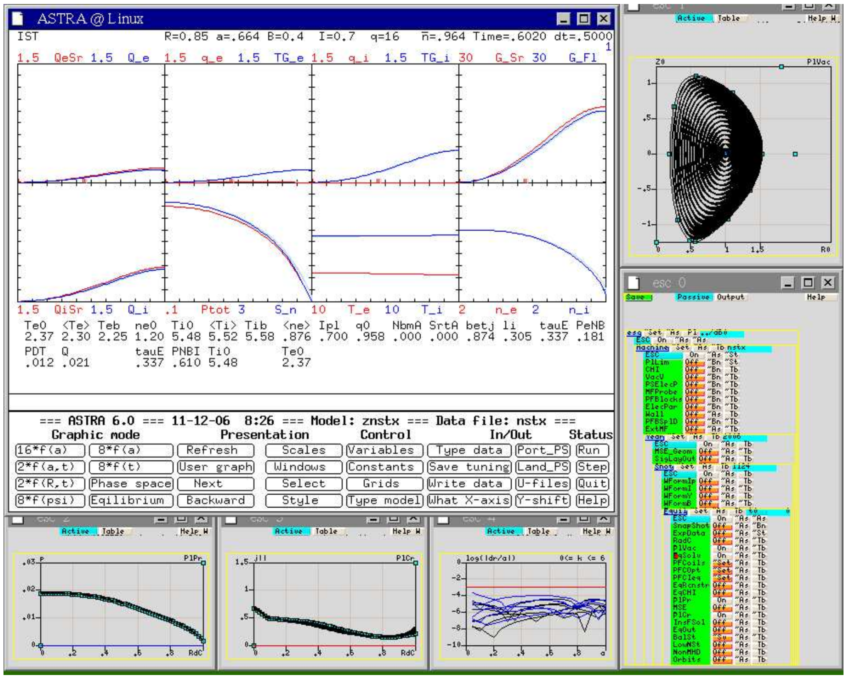
within TFTR stability limits, and with small PFC load (< 5 MW)

	PNBI	n	T	P DT	Q DT	tauE	nend	Ti0	Te0	gb %
(a)	1.65	0.3	10	15.4	9.34	6.54	0.42	18.7	14.8	1.64
(c)	3.30	0.3	10	35.5	10.6	4.04	0.55	17.6	13.6	1.96
(d)	4.16	0.3	10	48.9	11.6	3.58	0.59	17.5	13.4	1.96

The "brute force" approach ($P_{NBI} = 40$ MW) did not work on TFTR for getting $Q_{DT} = 1$. With $P_{DT} = 10.5$ MW only $Q_{DT} = 0.25$ was achieved.

In the LiWall regime, using less power, TFTR could easily challenge even the $Q = 10$ goal of ITER

ASTRA-ESC simulations of NSTX, B=0.4 T, I=0.7 MA, 20 keV NBI, 0.6 MW



Hot-ion mode:

$T_i = 5.5$ [keV],
$T_e = 2.5$ [keV],
$n_e(0) = 0.12 \cdot 10^{20}$,
$\tau_E = 0.33$ [sec],
$P_{NBI} = 0.61$ [MW]

NBI energy should be consistent with the plasma temperature:

$E_{NBI} = 2.5(T_i + T_e)$

Good confinement is a key for solving the power extraction problem

Plasma edge temperature is determined by the particle flux

S. Krasheninnikov's boundary conditions (not of the "experts" in transport)

$$\frac{5}{2}\Gamma_e^{wall} T_e^{edge} = \int_V P_e dV, \qquad \frac{5}{2}\Gamma_i^{wall} T_i^{edge} = \int_V P_i dV$$

Recycling R determines the relation between plasma particle fluxes to the edge Γ_e, Γ_i and to the wall $\Gamma_e^{wall}, \Gamma_e^{wall}$

$$\Gamma_e = (1-R)\Gamma_e^{wall}, \qquad \Gamma_i = (1-R)\Gamma_i^{wall}, \qquad \Gamma_{e,i}^{wall} = \frac{1}{1-R}\Gamma_{e,i}$$

Low recycling lead to elimination of the thermo-conduction in energy transport

$$\underbrace{\frac{5}{2}\oint \Gamma_{i,e} T^{i,e} dS}_{convection} + \underbrace{\oint q_{i,e} dS}_{thermo-conduction} = \underbrace{\int_0^V P_{i,e}(V) dV}_{Power\ source}, \qquad \underbrace{\oint q_{i,e} dS}_{thermo-conduction} \simeq 0, \qquad T_{i,e}^{edge} \simeq T_{i,e}(0)$$

The energy losses from the plasma are exclusively convective and, thus, determined by the best confined component (ions).

The LiWF introduces in fusion the best possible confinement regime

Independence of T^{edge} on the RMF is a direct indication that the boundary condition, rather than "transport barrier", determines T^{edge}

The reference transport model for LiWall regime

Heat flux:

$$\mathrm{q}_i = \chi_i^{neo} \nabla T_i$$ *neo-classical ions, plays no role,*

$$\mathrm{q}_e = \chi_i^{neo} \nabla T_e$$ *"anomalous" electrons, plays no role*,

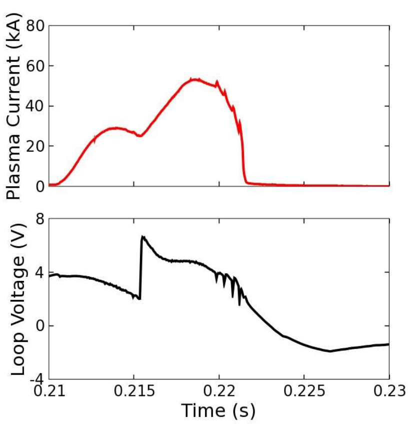
Particle flux:

$$\Gamma_{i,e} = \chi_i^{neo} \nabla n$$ *(Ware pinch neglected)*

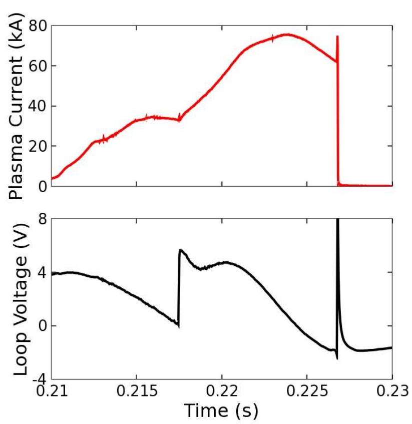
The LiWF does not assume anything regarding confinement of electrons

MMF relies exclusively on the "science" of scalings. At the same time, it has no representative database for its "hot-electron" mode

In LiWF there is no tendency of the current peaking



Treasurous (for endless MHD studies) pre-Li CDX-U regimes

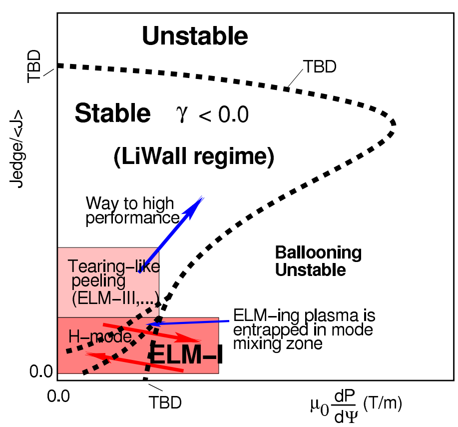


"Meaningless" for theory MHD-free Li regimes

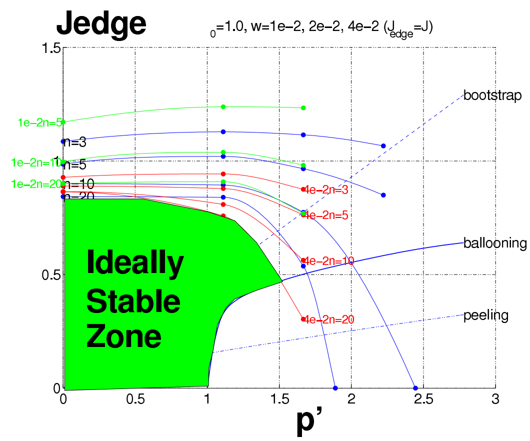
Together with the $q = 1$ surface, the LiWall regime wipes out the very opportunity for sawteeth and IRE

DIII-D discovery of the quiescent H-mode in 1999 was a shock for MHD theory

In a wide range, the finite current density at separatrix is stabilizing for ELMs. Pressure is destabilizing. (MMF's stability "experts" are still talking about "peeling" modes)



"Heuristic diagram" (Zakharov, 2005)



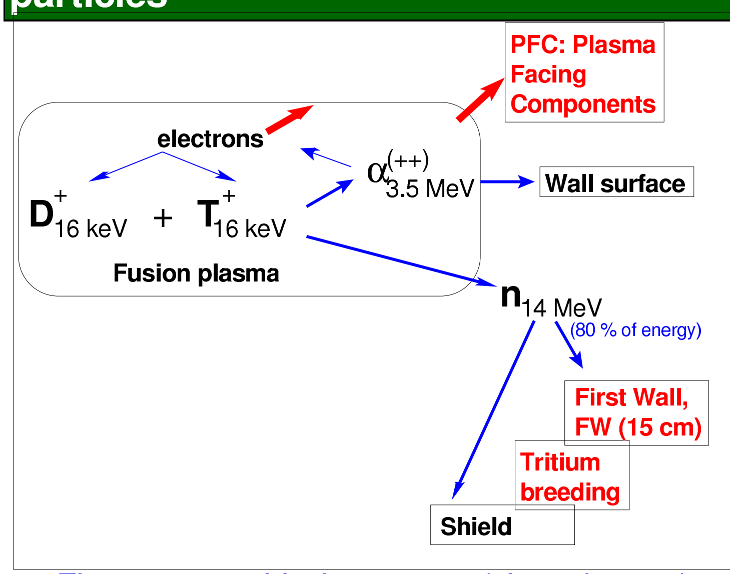
Keldysh Institute calculation, (Medvedev, 2003)

High temperature of LiWF is consistent with the high performance spot on stability diagram

MMF is pushing operational point directly into the mess of ELMs

3 Two approaches to fusion.

Mainstream Magnetic Fusion (MMF) relies on plasma heating by α-particles



Flow pattern of fusion energy (since the 50s)

Ignition criterion:

$$f_{pk}\cdot\langle p\rangle \cdot\tau_E^* = 1$$
[MPa · sec]

Peaking factor f_{pk}:

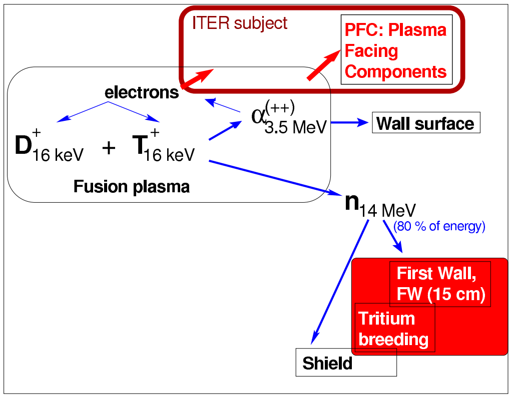
$$f_{pk} \equiv \frac{\langle 16 p_D p_T\rangle}{\langle p\rangle^2}$$

Plasma pressure p:

$$p = p_e + p_D + p_T + p_\alpha + p_I$$

MMF never approached the nuclear issues of a reactor

Its next step is still dealing with the plasma physics issues



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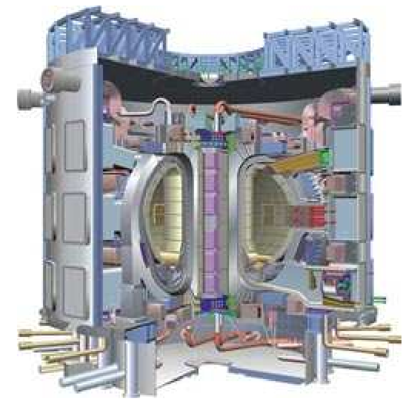
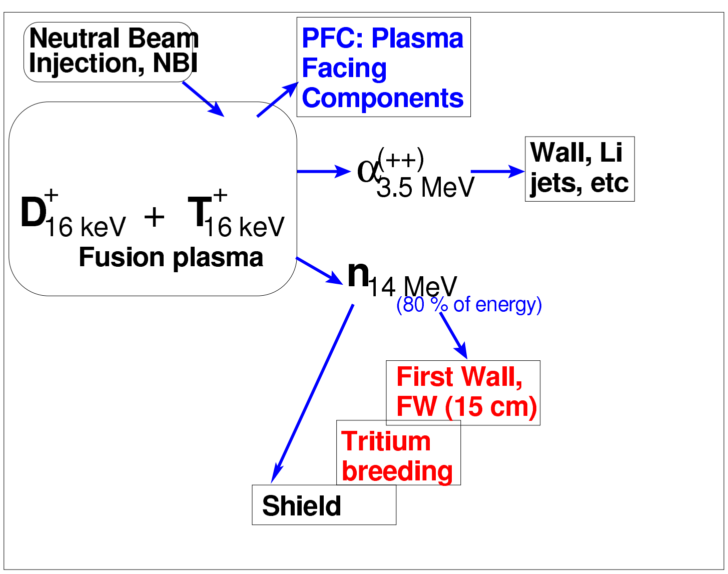


Even in the foreseeable future of MMF

ITER targets the α-heating dominated regime

The sizes are too big, the neutron flux is too low for addressing the nuclear technology issues

The LiWall Fusion (LiWF) relies on NBI and Li pumping walls



Clean flow pattern of fusion energy in LiWall concept

α-particles are free to go out of plasma

NBI controls both the temperature and the density

$$P_{NBI} = \frac{3}{2}\frac{\langle p\rangle V_{pl}}{\tau_E},$$

$$\frac{dN_{NBI}}{dt} = \Gamma^{ions}_{core\rightarrow\ edge}$$

Super-Critical Ignition (SCI) confinement is necessary to make NBI work this way

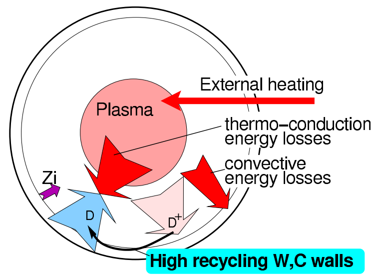
$$\tau_E >> \tau_E^*$$

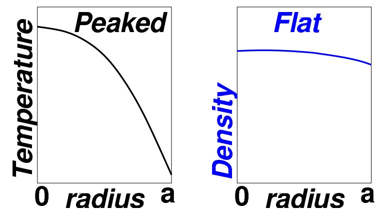
Plasma physics issues, unhandable by MMF, disappear in LiWF

LiWF is suitable for reactor design issues

The right plasma-wall contact is the key to magnetic fusion

MMF requires a low temperature plasma edge

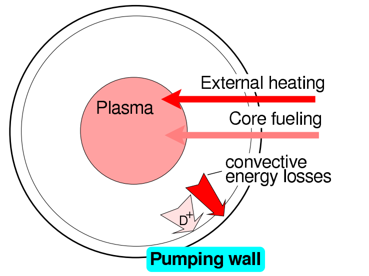


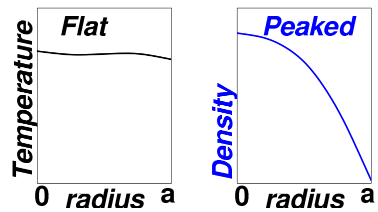


As a “gift” from plasma physics MMF gets ITG/ETG turbulent transport.

Most of the plasma volume does not produce fusion

Molten Li pumps the plasma out. High edge T is OK





No “gifts” from plasma physics (ITG/ETG, sawteeth, ELMs) are expected or accepted.

Reliance only on external control.

The entire plasma volume produces fusion

Pumping walls simplify the entire picture of plasma wall interactions

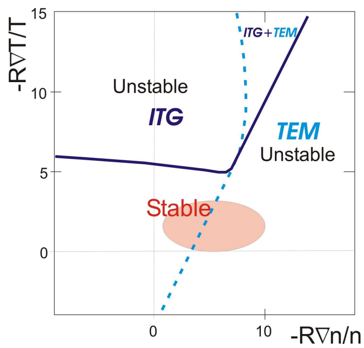
As a fusion concept, LiWF development in short time accomplished much more than MMF for 40 years

Issue	MMF	LiF
Use of plasma volume	25-0.30 %	100 %
Fusion producing β_{DT}	$\beta_{DT} < 0.5\beta$	$\beta_{DT} > 0.5\beta$
Anomalous electrons	YES	NO
Transport data base	not scalable	scalable from small devices
Sawteeth	unpredictable	absent
ELMs	unpredictable	absent
Fueling	unresolvable	existing NBI technology
Fusion power control	unpredictable	existing NBI technology
Edge pressure control	reduced performance	RMF, NBI technology
Power extraction	unresolvable	conventional technology
Tritium control	tritium in all channels	pumping by Li

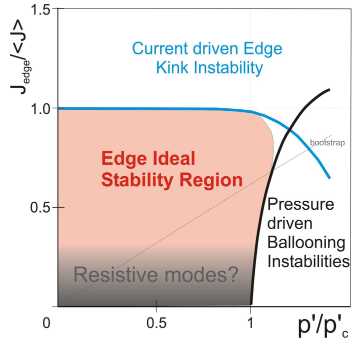
As a reactor concept, the Mainstream fusion is full of junk ideas valuable only for endless “scientific” studies and for science history museums

Recent NSTX forum clearly indicated that the NSTX program is already exhausted. It's time to change it.

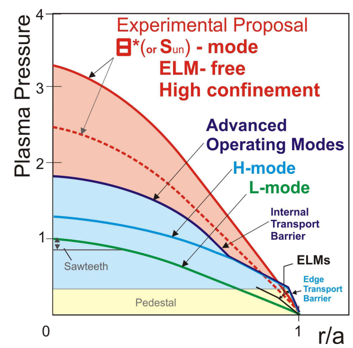
LiWF suggests a new area of research relevant to the reactor development



Transport operational space (C.Bourdelle, JET)



Edge stability operational space (LZ, S.Medvedev, Keldysh)



LiWF pressure profile (by S.Gerasimov from JET#JG03.35-27c)

Even for ITER LiWF can propose real solutions of its hot problems (e.g., ELMs, sawteeth, ignition, power extraction).

LiWF plasma regimes are consistent with the power extraction by Li PFC

Several hardware modification should be performed on the device

1. Transition to the molten lithium. Testing (at the end of the campaign) of a Li preloaded Li/SS/Cu plate.
2. Transition to the low energy NBI injection.
3. Transition to the capillary system in the low divertor with external supply and extraction of lithium
4. The challenging (if any) issue might be the secondary electron emission from the plate.

In this new capacity the device can serve as a motivational STep0 for 3 step program for the Reactor Development Facility